ELECTRICAL DEVICES AND CIRCUITS FOR LOW TEMPERATURE SPACE APPLICATIONS

R.L. Patterson[1], A. Hammoud[2], J.E. Dickman[1], S. Gerber[3], M.E. Elbuluk[4], & E. Overton[1]

[1]NASA Glenn Research Center, Cleveland, Ohio 44135, USA
[2]QSS Group, Inc., NASA Glenn Research Center, Cleveland, Ohio 44135, USA
[3]ZIN Technologies, Inc., NASA Glenn Research Center, Cleveland, Ohio 44135, USA
[4]University of Akron, Department of Electrical Engineering, Akron, OH 44325, USA

ABSTRACT

The environmental temperature in many NASA missions, such as deep space probes and outer planetary exploration, is significantly below the range for which conventional commercial-off-the-shelf electronics is designed. Presently, spacecraft operating in the cold environment of such deep space missions carry a large number of radioisotope or other heating units in order to maintain the surrounding temperature of the on-board electronics at approximately 20 °C. Electronic devices and circuits capable of operation at cryogenic temperatures will not only tolerate the harsh environment of deep space but also will reduce system size and weight by eliminating or reducing the heating units and their associate structures; thereby reducing system development cost as well as launch costs. In addition, power electronic circuits designed for operation at low temperatures are expected to result in more efficient systems than those at room temperature. This improvement results from better behavior in the electrical and thermal properties of some semiconductor and dielectric materials at low temperatures. An on-going research and development program on low temperature electronics at the NASA Glenn Research Center focuses on the development of efficient electrical systems and circuits capable of surviving and exploiting the advantages of low temperature environments. An overview of the program will be presented in this paper. A description of the low temperature test facilities along with selected data obtained from in-house component testing will also be discussed. On-going research activities that are being performed in collaboration with various organizations will also be presented.

INTRODUCTION

Electronics capable of low temperature operation are required for many future NASA space missions where it is desirable to have smaller, lighter, and cheaper (unheated) spacecraft. These include Mars orbiters, landers, and rovers; Europa oceanic exploratory probes and instrumentation; and outer planetary exploration and deep space probes. Table 1 shows operational temperatures for unheated spacecraft in the environments of the outer planets. For example, an inter-planetary probe launched to explore the rings of Saturn would experience a temperature near Saturn of about –183 °C. In addition to surviving the space hostile environments, electronics capable of low temperature operation would contribute to improving circuit performance, increasing system efficiency, and reducing development and launch costs.

Presently, spacecraft operating in the cold environment of deep space carry on-board a large number of radioisotope heating units (RHUs) to maintain an operating temperature for the electronics at approximately 20 °C. This is not an ideal solution because the radioisotope heating units are always producing heat, even when the spacecraft may already be too hot, thus requiring an active thermal control system for the spacecraft[1]. In addition, RHUs add cost and require elaborate containment structures. Electronics capable of operation at cryogenic temperatures will not only tolerate the hostile environment of deep space but also reduce system size and weight by eliminating radioisotope heating units and associated

Table 1: *Typical operational temperatures for unheated spacecraft*

Mission	Temperature °C
Mars	-20 to –120
Jupiter	-151
Saturn	-183
Uranus	-209
Neptune	-222
Pluto	-229

[1] *Contact information for R.L. Patterson-Email: Richard.patterson@grc.nasa.gov*

structures; thereby reducing system development and launch costs, improving reliability and lifetime, and increasing energy densities.

In addition to deep space applications, low temperature electronics have potential uses in terrestrial applications that include magnetic levitation transportation systems, medical diagnostics, cryogenic instrumentation, and super-conducting magnetic energy storage systems. The utilization of power electronics designed for and operated at low temperature is expected to result in more efficient systems than room temperature systems. This improvement results from better electronic, electrical, and thermal properties of certain materials at low temperatures[2,3]. In particular, the performance of certain semiconductor devices improves with decreasing temperature down to liquid nitrogen temperature (-196 °C). At low temperatures, majority carrier devices demonstrate reduced leakage current and reduced latch-up susceptibility[3,4]. In addition, these devices show higher speed resulting from increased carrier mobility and saturation velocity[3-5]. An example is the power MOSFET which has lower conduction losses at low temperature due to the reduction in the drain-to-source resistance RDS(on) resulting from increased carrier mobility[4,6,7].

NASA GRC LOW TEMPERATURE ELECTRONICS PROGRAM

The Low Temperature Electronics Program at the NASA Glenn Research Center (GRC) focuses on research and development of electrical components and systems suitable for applications in deep space missions. Research is being conducted on devices and circuits for use down to cryogenic temperature (-196 °C). The goal of the low temperature electronics program is to develop and demonstrate reliable, efficient, power systems capable of surviving and exploiting the advantages of low temperature environments. The targeted systems are mission-driven and include converters, inverters, controls, digital circuits, and special-purpose circuits. Initial development efforts have produced the successful demonstration of low temperature operation and cold-restart of several DC/DC converters (with outputs from 5 to 1000 Watts) utilizing different design topologies[1,4,7]. Some of these circuits employed superconducting inductors.

In support of system development, device and component research and development efforts are underway in critical areas of passive and active components, and energy generation and storage. Initially, commercial-off-the-shelf (COTS) devices and components are characterized in terms of their performance at low-temperatures. When viable commercial devices fail to meet mission requirements, efforts are then undertaken to develop advanced components.

In addition to the development efforts to fill the technology gaps in low temperature power electronics, thermal issues relating to packaging, integration, and cycling are being explored.

GRC LOW TEMPERATURE FACILITIES

At NASA Glenn Research Center, facilities exist for the testing of power and control circuits operating from DC to several Megahertz over a wide temperature range. These facilities consist of several liquid nitrogen cooled environmental chambers in which a circuit can be operated with controlled temperature in the range of 300 °C to -196 °C. The chambers have built-in controllers that allow selecting the desired temperature rate of change as well as soak times. Computer-controlled instrumentation is interfaced with the environmental chambers via IEEE 488 GPIB for data acquisition. Measurement equipment include a digital signal analyzer, pattern generators, precision digital RLC meters, high speed storage oscilloscopes, precision temperature controller and recorder, various electronic loads, and resistive loads from mW’s to kW’s in power.

Another unique computerized control system is used in conjunction with a cryopumped vacuum chamber containing a cryocooled sample holder for the characterization of commercial and developmental semiconductor devices and components. This facility is capable of *in-situ* I-V and C-V characterization of semiconductor devices from 23 °C to -248 °C.

GRC has designed computer-controlled facilities for low-temperature long term thermal cycling and characterization of electrical and physical properties of dielectrics and capacitors. In addition, facilities exist for reliability studies and life testing of passive and active devices in space-like environments under multi-stress conditions. Typical studies that can be carried out using these facilities include dielectric material characterization, DC and AC breakdown voltages, resistivity measurements, switching characteristics, and electronic system overall performance such as regulation and efficiency.

Other on-site supporting research facilities include physical, chemical, and mechanical test chambers and diagnosis stations. Characterization of materials and evaluation of systems and components under space-like environment, such as vacuum, plasma, ultraviolet radiation, and atomic oxygen, can be achieved in multi-stress aging test rigs and facilities.

LOW TEMPERATURE R&D ACTIVITIES

Some of the components that are being characterized include semiconductor switching devices, capacitors, batteries, temperature transducers, and A/D converters, to name a few. Figure 1 shows the change in capacitance for three types of capacitors in the temperature range of 25 °C to -190 °C at a frequency of 20 kHz. It can be seen clearly that while the mica capacitor exhibits excellent stability with temperature, the electrolytic tantalum capacitor undergoes significant decrease in capacitance when the test temperature goes below -25 °C. In fact, at temperatures below -80°C the capacitance drops to zero. Unlike its electrolytic counterpart, the solid tantalum capacitor exhibits only a slight decrease in capacitance as temperature is decreased. This reduction in capacitance amounts to only about 10% even down to -190 °C.

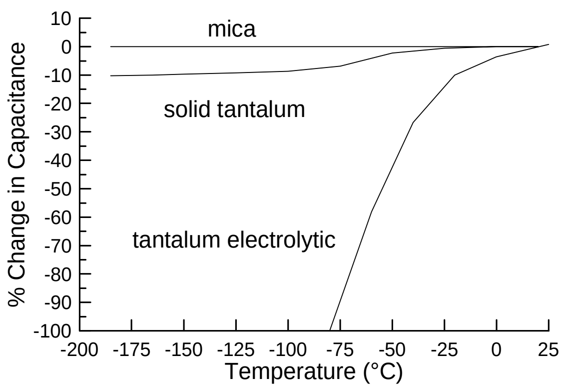

***Figure1**: Capacitance change with temperature for various types of capacitors.*

***Table 2**: Converted output voltage at various temperatures.*

Input (V)	Output (V) @ 25 °C	Output (V) @ -100 °C	Output (V) @ -190 °C
0	0.007	0.010	0.010
0.5	0.505	0.498	0.508
1	1.004	1.006	1.004
2	2.000	2.002	1.993
5	4.994	4.994	5.001
7.25	7.241	7.228	7.226
10	9.983	9.963	9.963
10.1	10.000	10.000	10.000

A commercial off-the-shelf 12-bit serial CMOS analog-to-digital converter, which was rated for operation between –40 °C and +85 °C, was evaluated from room temperature to –190 °C in a liquid nitrogen cooled chamber. Parameters investigated included voltage conversion and control signal timing at a switching frequency of 100 kHz. Although the device had a built-in internal voltage reference, tests were also carried out using an external voltage reference. In either case, the device was able to provide the voltage conversions throughout the entire test temperature range down to –190 °C. The converted output obtained using an external voltage reference, however, was more accurate than those obtained with an internal voltage reference. Results obtained at three different temperatures with an external reference are shown in Table 2.

Commercially available DC/DC converter modules were investigated for potential use at low temperatures. For example, the output voltage of a commercial DC/DC converter at various load levels is shown as a function of temperature in Figure 2. It can be seen that the output voltage of this particular module tended to be steady only between +20 °C and –20 °C. A slight reduction occurred in voltage regulation as temperature was further decreased to –80 °C. Below that temperature, the converter tended to become unstable in terms of voltage regulation. This behavior occurred regardless of the levels of the applied input voltage and connected output load. Another commercial DC/DC module included in this investigation faired relatively well in terms of its output regulation with temperature. The output voltage of this converter is depicted in Figure 3 as a function of temperature at various load levels.

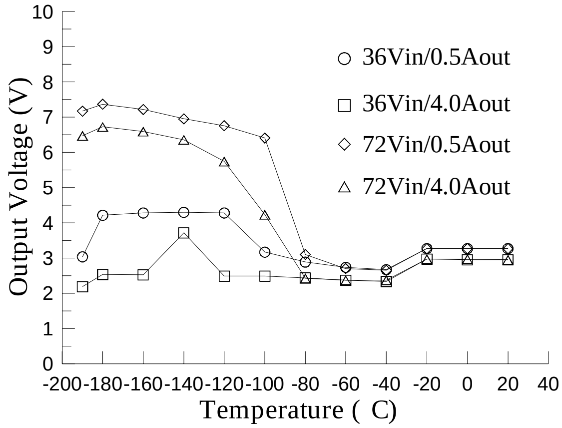

***Figure 2**: Poor performance of one commercial dc/dc converter module.*

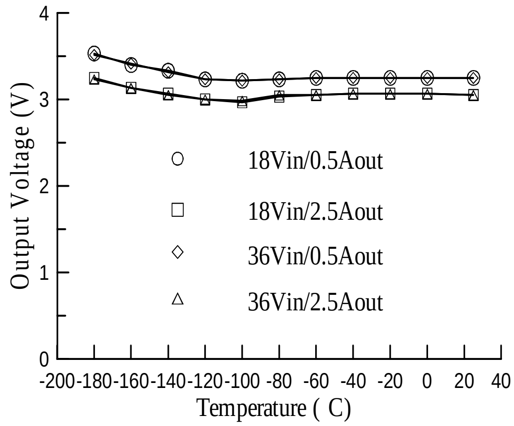

***Figure 3**: Superior performance of another commercial dc/dc converter.*

Current-mode and voltage-mode pulse width modulation controllers were evaluated extensively for low temperature operation. The performance of one of those commercial grade pulse width modulation controller chips was evaluated between 25 °C and -190 °C. The device displayed acceptable performance throughout the entire test temperature range. Waveforms of the device reference voltage, oscillator, and output switching voltage, which were recorded at a control voltage (VC) of 1.5V, are shown in Figures 4a and 4b at test temperature of 25 °C and -190 °C, respectively. It can be seen clearly that all investigated properties did not undergo much change with temperature, as evident from the similarity of the waveforms shown for both extreme temperature, i.e. 25 °C and –190 °C.

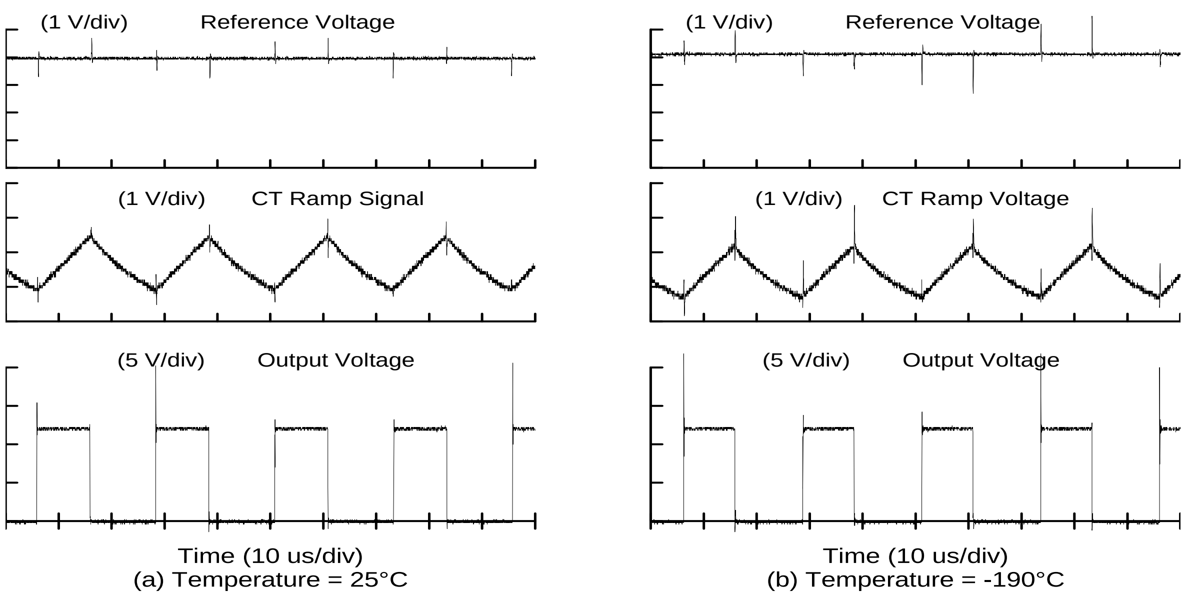

***Figure 4**: Waveforms of PWM controller at (a) 25 °C and (b) -190 °C.*

The performance of three precision oscillators was investigated at low temperatures. One uncompensated oscillator was able to function to -196 °C. A second uncompensated oscillator was built to operate at ultra-low temperatures, and it operated down to -263 °C. A third oscillator, which was temperature compensated and modified for low temperature use, operated within 0.3 ppm in frequency down to -160 °C. The normalized output frequencies of the three oscillators are shown as a function of temperature in Figure 5.

Figure 6 shows the drain-to-source on-state resistance (R_{DS}(on)) versus temperature for two types of MOSFET devices. It can be seen that the standard as well as the silicon-on-insulator devices show similar behavior in their R_{DS} with temperature. The on-state resistance of either device seemed to decrease with decrease in temperature till about –170 °C. This trend, however, was reversed as the test temperature was decreased further as reflected by the slight increase in the on-state resistance of both devices. At any temperature, the SOI device exhibited a slightly higher on-state resistance than its standard counterpart.

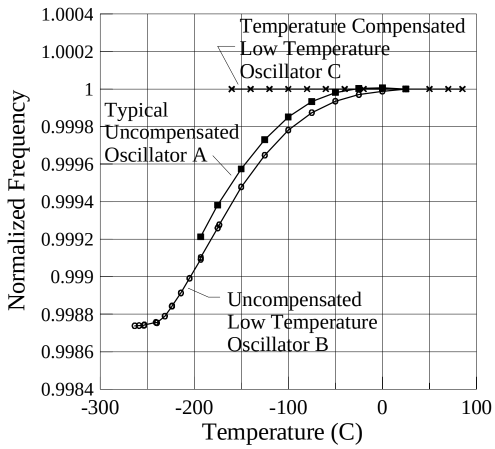

Figure 5*: Normalized frequency output for three types of oscillators.*

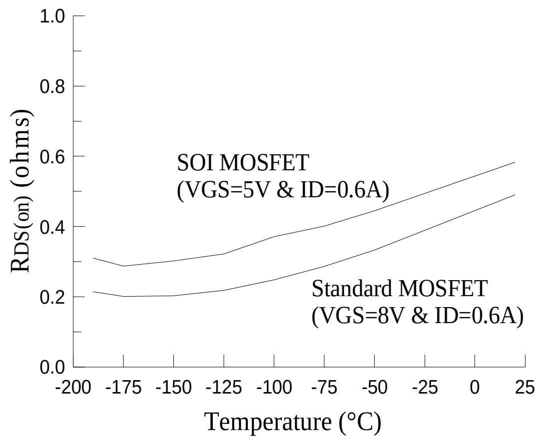

Figure 6*: Drain-to-source on-resistance for SOI and standard MOSFET devices versus temperature.*

CONCLUSION

An overview of the Low Temperature Electronics Program at NASA Glenn Research Center was given. The research efforts are focused on developing selected, mission-driven, power systems and supporting technologies for low temperature operation. The on-going activities include dielectric and insulating material research and evaluation, development and testing of low temperature power components, and electronic system integration and demonstration. Other supporting research investigations comprise long term reliability assessment of power devices and integrated circuits and the effects of low temperature exposure on device interconnect and packaging. These research and development efforts are performed in collaboration with other agencies, academia, and the aerospace industry in order to meet the needs of future space power and other electrical systems.

REFERENCES

1. S.S. Gerber, R.L. Patterson, B. Ray and C. Stell, *Performance of a spacecraft DC/DC converter breadboard modified for low temperature operation*, IECEC 96, 1, 592-598, 1996.
2. R.K. Kirschman, *Low temperature electronic device operation*, Symposium of Electrochemical Society, 14, 1991.
3. M. Dean, D. Foty, N. Saks, S. Raider, and G. Oleszel, *Low temperature microelectronics: opportunities and challenges*, Proc. Symposium on Low Temperature Electronic Device Operation, Electrochemical Society, 91,14, 25-37, 1991.
4. B. Ray, S. S. Gerber, R. L. Patterson and I. T. Myers, *Power control electronics for cryogenic instrumentation*, Advances in Inst. and Control, 50, 1, Int. Soc. for Measurement and Control, 131-139, 1995.
5. R. K. Krishman, *Cold electronics: an overview*, Cryogenics, 25, 3, 115-122, 1985.
6. O. Mueller, *On-resistance, thermal resistance and reverse recovery time of power MOSFETs at 77K*, Cryogenics, 29, 1006-1014,1989.
7. B. Ray, S. S. Gerber, R.L. Patterson and I. T. Myers, *77K Operation of a multi-resonant power converter*, IEEE PESC’95 Record, 1, 55-60, 1995.